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13. ABSTRACT *(Maximum 200 words)*

Introduction: We studied the efficiency of liquid cooling garments (LCG) and its relationship to the insulation of outer clothing, perfusate inlet temperatures and environmental conditions by both theoretical analysis and thermal manikin (TM) testing.

Methods: an equation to estimate LCG cooling efficiency was developed on the basis of energy balance. The efficiency is a function of the thermal resistance between the TM skin and perfusate in the LCG, the thermal resistance between the environment and the perfusate, as well as TM skin, ambient and perfusate temperatures. Three ensembles: cooling vest (CV) only, CV plus a battle dress uniform (CVB), and CVB plus a battle dress overgarment (CVO), were tested on a sweating TM in dry and wet conditions. The TM surface temperature was maintained at 33°C and the environment was 30°C and 50% r.h. The LCG heat removal from TM was calculated using the power inputs to TM with and without perfusate flow.

Results and Conclusion: The cooling efficiency was increased from ~0.45 for CV to ~0.70 for CVO in dry experiments and from ~0.53 for CV to 0.78 for CVO in wet experiments. With additional outer clothing layers, higher thermal resistances increased the rate of heat removal from TM surface, and decreased heat gain from the ambient environment, thus increasing efficiency. The perfusate inlet temperature had minimal influence on the efficiency. The equations developed can predict the cooling efficiency and heat removal rates under wider range of environmental conditions.

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Efficiency of Liquid Cooling Garments: Prediction and Manikin Measurement

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Introduction: We studied the efficiency of liquid cooling garments (LCG) and their relationship to the insulation of outer clothing, perfusate inlet temperatures, and environmental conditions by both theoretical analysis and thermal manikin (TM) testing. **Methods:** An equation to estimate LCG cooling efficiency was developed on the basis of energy balance. Cooling efficiency is a function of the thermal resistance between the TM skin and perfusate in the LCG, the thermal resistance between the environment and the perfusate, and TM skin, ambient, and perfusate temperatures. Three ensembles, a cooling vest (CV) only, CV plus a battle dress uniform (CVB), and CVB plus a battle dress overgarment (CVO), were tested on a sweating TM in dry and wet conditions. The TM surface temperature was maintained at 33°C and the environment was 30°C and 50% RH. The LCG heat removal from the TM was calculated using the power inputs to the TM with and without perfusate flow. **Results:** The cooling efficiency was increased from ~0.45 for CV to ~0.70 for CVO in dry experiments and from ~0.53 for CV to 0.78 for CVO in wet experiments. **Conclusion:** With additional outer clothing layers, higher thermal resistances increased the rate of heat removal from the TM surface, and decreased heat gain from the ambient environment, thus increasing efficiency. The perfusate inlet temperature had minimal influence on the efficiency. The equations developed can predict cooling efficiency and heat removal rates under a wider range of environmental conditions.

Keywords: thermal manikin, heat stress, heat transfer, protective clothing.

HEAT STRESS IS A major environmental threat to outdoor industrial and agricultural activities, and military operations in hot environments. The threat becomes more severe for tasks that require wearing personal protective equipment. An effective way to reduce heat stress, prevent heat injury, and/or extend endurance time is to use a microclimate cooling system (MCS). The capabilities of an MCS are limited by factors such as power supply, weight, volume, etc., and, therefore, a high system efficiency is necessary to make the MCS operational feasible.

Only a portion of total liquid cooling garment (LCG) cooling can actually reduce heat stress in the human body. Since perfusate inlet temperature (T_{in}) is lower than both skin and ambient temperatures, the perfusate circulating within the LCG absorbs heat from both the body and the ambient environment. The concept of LCG cooling efficiency, defined as the fraction of cooling that goes to the human (Teal W. Unpublished study, 2002), was introduced to quantify this relationship. From the perspective of heat transfer, the efficiency of

the MCS system is influenced by properties of the LCG itself, the clothing ensemble worn over the LCG (outer clothing, e.g., personal protective equipment), and environmental conditions.

Thermal manikins (TM) have been used to measure LCG heat removal rates since the 1970s (4). Semi-empirical equations have been developed to predict LCG heat removal rates (2,5,7,8). A standard for measuring the heat removal rate of a personal cooling system using a sweating heated manikin is being developed by the American Society for Testing and Materials (ASTM) to standardize the measurement procedure (ASTM WK523. Test method for measuring the heat removal rate of personal cooling systems using a sweating heated manikin. Work item, 2003). These works focus only on LCG heat removal rates, and thus do not address cooling efficiency. Together the heat removal rate and cooling efficiency provide a more accurate description of LCG performance and are both necessary to design and optimize the MCS performance. However, there is a lack of information on cooling efficiency. The purpose of this study was to examine cooling efficiency and its relationship to the insulation of outer clothing, perfusate inlet temperatures, and environmental conditions through theoretical analysis and TM measurements.

METHODS

Heat Transfer Analysis

Fig. 1 shows the heat transfer processes that occur between the skin, LCG, outer clothing, and the ambient environment. The human body dissipates heat from the skin through LCG/outer clothing to the ambient envi-
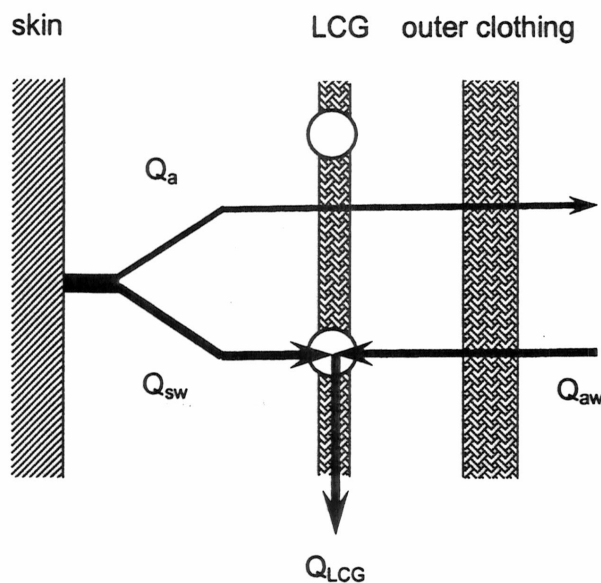
Fig. 1. Heat transfer processes between the skin, liquid cooling garments (LCG), outer clothing, and ambient environment. Q_a: heat transfer from the human skin through LCG/outer clothing into the ambient environment; Q_{sw}: LCG heat removal from the human body or manikin; Q_{aw}: LCG heat gain from the ambient environment to the LCG; Q_{LCG}: total LCG heat removal.

ronment (Q_a) and dissipates heat from the skin to the perfusate in the LCG (Q_{sw}). The LCG also absorbs heat from the ambient environment through the outer clothing (Q_{aw}). Therefore, the total heat removal rate by LCG (Q_{LCG}) consists of two components:

$$Q_{LCG} = Q_{sw} + Q_{aw} \qquad \text{Eq. 1}$$

As explained below, Q_{sw} is obtained from TM measurements. Q_{LCG} is calculated from the measurement of inlet and outlet temperatures and flow rates:

$$Q_{LCG} = \dot{m}c_p(T_{out} - T_{in}) \qquad \text{Eq. 2}$$

where $\dot{m}$ is flow rate in $kg \cdot s^{-1}$; c_p is the specific heat capacity of water ($4.18\ KJ \cdot kg^{-1} \cdot {}^\circ C^{-1}$); T_{out} is perfusate outlet temperature in $^\circ C$; and T_{in} is perfusate inlet temperature in $^\circ C$.

According to the definition, the cooling efficiency (η) is expressed as:

$$\eta = \frac{Q_{sw}}{Q_{LCG}} \qquad \text{Eq. 3}$$

Further assuming that heat exchange is in steady state, the heat removal from the human body or TM and heat gain from the ambient environment are given by:

$$Q_{sw} = \frac{T_s - T_w}{R_{sw}}A \qquad \text{Eq. 4}$$

$$Q_{aw} = \frac{T_a - T_w}{R_{aw}}A \qquad \text{Eq. 5}$$

where T_s is the skin temperature in $^\circ C$; T_w is the average perfusate temperature in $^\circ C$; T_a is the ambient temperature in $^\circ C$; R_{sw} is the thermal resistance between the TM skin and perfusate in LCG in $m^2 \cdot {}^\circ C \cdot W^{-1}$; R_{aw} is the thermal resistance between the ambient environment and the perfusate in LCG in $m^2 \cdot {}^\circ C \cdot W^{-1}$; and A

is the body surface area covered by LCG in m^2. Consequently, Eq. 3 is re-written as:

$$\eta = \frac{Q_{sw}}{Q_{sw} + Q_{aw}} = \frac{1}{1 + \dfrac{T_a - T_w}{T_s - T_w} \cdot \dfrac{R_{sw}}{R_{aw}}} \qquad \text{Eq. 6}$$

Thermal Manikin Measurements

The TM at our Institute has 18 independently heated thermal zones plus an additional heated guard zone at the neck mounting plate. Sixteen of the zones are wet zones with an integrated sweating dispenser. The set points for water flow in each zone are adjusted to keep the TM skin saturated. The TM is covered with a cotton skin layer to distribute water over the zone surface. The ThermDAC software (Measurement Technology Northwest, Seattle, WA) controls, records data, and displays real-time numerical and graphical plots of section temperatures. The software also calculates thermal resistances, evaporative resistances, and power input into the manikin.

TM tests were run on dry skin (i.e., no sweating) and wet skin (i.e., sweating), respectively. The TM surface temperature was maintained at 33°C during all tests and the environment in the climatic chamber was controlled at a temperature of $30 \pm 0.5°C$, a relative humidity of $50 \pm 5\%$, and a wind speed of $0.4\ m \cdot s^{-1}$. After the clothing ensemble was placed on the TM, baseline values were measured without any perfusate flowing through the LCG after steady-state condition was achieved. The cooling system was then turned on to circulate cool perfusate. When a new steady-state condition was reached in 1 to 2 h, measurements were taken again. The perfusate inlet temperatures (T_{in}) were 15, 20, and 25°C, respectively, and the flow rate $\dot{m}$ was $0.0083\ kg \cdot s^{-1}$ ($0.5\ L \cdot min^{-1}$).

Experimentally, Q_{sw} was calculated using the difference between the powers input to the TM with the flowing perfusate (i.e., active LCG) and without flowing perfusate (i.e., inactive LCG). Q_{LCG} was calculated by Eq. 2. Then Q_{aw} was calculated by subtracting Q_{sw} from Q_{LCG} using Eq. 1. R_{sw} and R_{aw} were calculated using Eq. 4 and 5. Only the TM torso front, torso back, abdomen, right hip, and left hip sections were covered by the cooling vest. Therefore, only measurements from these sections were used in the calculation and analysis. The total surface area of these sections, i.e., A, was $0.611\ m^2$.

Clothing Ensembles

Three ensembles consisting of an air warrior microclimate cooling garment, i.e., cooling vest (CV) only, a CV plus battle dress uniform (CVB), and the CVB layers plus battle dress overgarment (CVO), were tested on the TM. The CV consists of a cotton vest and ~31 m tubing (tube internal/external diameters ~2.5/4 mm and spacing between tubes ~20–30 mm) sewn inside the vest. The total thermal resistances of the battle dress uniform and the battle dress overgarment were 0.22 and $0.26\ m^2 \cdot {}^\circ C \cdot W^{-1}$, respectively.

RESULTS

Table I gives the heat transfer properties of the three ensembles with and without perfusate (empty) in the

TABLE I. HEAT TRANSFER PROPERTIES OF THE LCG ENSEMBLES AS MEASURED ON THE TM.

	Thermal Resistance ($m^2 \cdot °C \cdot W^{-1}$)		Evaporative Resistance ($m^2 \cdot Pa \cdot W^{-1}$)
	Stationary Air in Tubes	Stationary Perfusate in Tubes	Stationary Air in Tubes
CV	0.28	0.24	43.11
CVB	0.39	0.35	65.25
CVO	0.60	0.51	101.45

For the nude thermal manikin (TM), the thermal resistance of the torso area is 0.15 $m^2 \cdot °C \cdot W^{-1}$ and the evaporative resistance is 20.58 $m^2 \cdot Pa \cdot W^{-1}$. LCG = liquid cooling garment; CV = cooling vest only; CVB = CV plus battle dress; CVO = CVB plus battle dress overgarment.

CV. Both thermal and vapor resistances increased when outer clothing was worn over the CV. When perfusate filled the CV, thermal resistances were reduced by 10–15%, as the perfusate inside the tubing increased heat conduction from the TM to the environment. Evaporative resistances were measured only without perfusate, as perfusate inside the tubing does not affect vapor transfer from the TM surface to the environment.

Fig. 2 and 3 illustrate total heat removal rates, which consists of heat removal from the TM and heat gain from the ambient environment for these three ensembles at three perfusate inlet temperatures in both the dry and wet experiments. The results demonstrate the effect of outer clothing insulation, perfusate inlet tem-
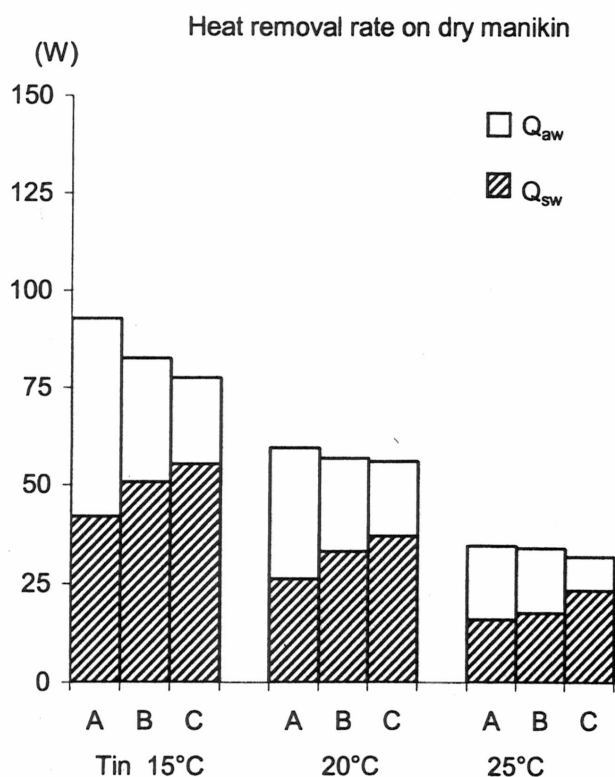
Heat removal rate on wet manikin

Fig. 3. Heat removal rates for A) the cooling vest (CV); B) CV plus battle dress uniform (CVB); and C) CVB plus battle dress overgarment (CVO) at three water inlet temperatures in the wet (sweating) experiments. Q_{sw}: LCG heat removal from the human body or manikin; Q_{aw}: LCG heat gain from the ambient environment to the LCG.

perature, and TM surface conditions on the heat removal rates. When outer clothing was worn over the CV and the outer insulation was increased, the heat removal from the TM, i.e., Q_{sw}, increased and the heat gain from the ambient environment, i.e., Q_{aw}, decreased, but the total heat removal, i.e., Q_{LCG}, changed only slightly. For example, at a T_{in} of 15°C in the wet experiments, Q_{sw} was ~67 W for CV, 86 W for CVB, and ~107 W for CVO, while Q_{LCG} varied from 134 W to 140 W. Heat removal in the wet (sweating) experiments was higher than in the dry experiments, and it was about 20–40% higher at a T_{in} of 20°C. Heat removal rates were also influenced by T_{in}, and increased when T_{in} decreased.

The measured heat removal rates in Fig. 2 and 3 were used to calculate the cooling efficiency. The results are presented in **Table II**. In dry experiments, the cooling efficiency was ~0.45 for the CV only, and increased to
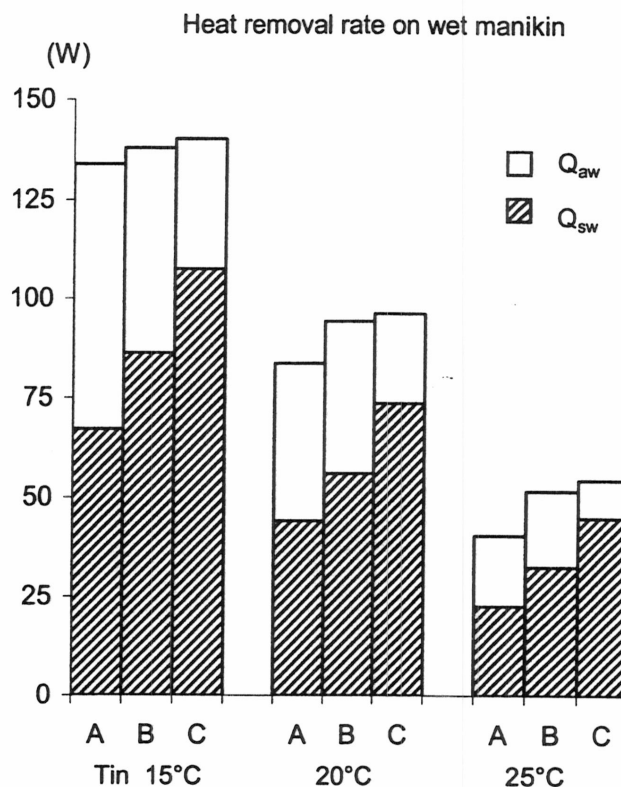
Heat removal rate on dry manikin

Fig. 2. Heat removal rates for A) the cooling vest (CV); B) CV plus battle dress uniform (CVB); and C) CVB plus battle dress overgarment (CVO) at three water inlet temperatures in dry experiments. Q_{sw}: LCG heat removal from the human body or manikin; Q_{aw}: LCG heat gain from the ambient environment to the LCG.

TABLE II. COOLING EFFICIENCIES IN THE DRY AND WET EXPERIMENTS.

	Dry T_{in}			Wet T_{in}		
	15 °C	20 °C	25 °C	15 °C	20 °C	25 °C
CV	0.45	0.44	0.46	0.50	0.53	0.56
CVB	0.62	0.58	0.52	0.63	0.64	0.63
CVO	0.71	0.66	0.73	0.77	0.77	0.82

T_{in} = inlet temperature; CV = cooling vest only; CVB = CV plus battle dress; CVO = CVB plus battle dress overgarment.

TABLE III. THERMAL RESISTANCES ($M \cdot °C \cdot W^{-1}$) REQUIRED FOR COOLING EFFICIENCY PREDICTION.

	Dry		Wet	
	R_{sw}	R_{aw}	R_{sw}	R_{aw}
CV	0.290	0.176	0.186	0.155
CVB	0.245	0.244	0.146	0.166
CVO	0.205	0.364	0.106	0.290

R_{sw} = thermal resistance between the TM skin and perfusate in the LCG; R_{aw} = thermal resistance between the ambient environment and the perfusate in the LCG; CV = cooling vest only; CVB = CV plus battle dress; CVO = CVB plus battle dress overgarment.

~0.70 when the battle dress uniform was worn over the CV, adding ~0.32 $m^2 \cdot °C \cdot W^{-1}$ of insulation. In the wet (sweating) experiments, the cooling efficiency was ~0.53 for CV only, and increased to ~0.78 when the battle dress uniform (CVB) and battle dress overgarment (CVO) were worn over the CV. The efficiencies in the wet (sweating) experiments were also higher than in the dry experiments. However, when T_{in} was varied, the cooling efficiencies remained nearly constant.

Thermal resistances between TM surface and perfusate, and between the ambient environment and perfusate were also calculated by Eq. 4 and 5, and the results are shown in **Table III**. When outer clothing was worn, the LCG was in closer contact with the TM surface and, therefore, R_{sw} decreased, but R_{aw} increased due to the additional insulation. In the wet (sweating) experiments, moisture enhanced heat conduction between the TM surface, LCG fabric, and inner layer of outer clothing. As a result, thermal resistances in the wet (sweating) experiments were lower than in the dry experiments.

DISCUSSION

This study investigated LCG cooling efficiency, heat removal rates, and their relationship to the insulation of outer clothing and perfusate inlet temperature through an integrated approach of theoretical analysis and TM measurement. TM measurements determined the heat removal rates and cooling efficiency, as well as the thermal and evaporative resistances. The derived equations, Eq. 4–6, together with measured thermal resistances as shown in Table III, can predict cooling efficiency and heat removal rates under wider non-test conditions. The integrated approach is both useful and necessary, as under certain environmental conditions, the TM test alone will not suffice. As an example, the TM tests cannot determine the heat removal rates in dry conditions when the ambient temperature (T_a) is higher than the TM skin temperature (T_s).

Our test protocol differs from the method used in the previous study by Dionne and colleagues (2) in respect to TM skin and ambient temperatures. In this study, TM skin temperature was 33°C and the ambient temperature was 30°C, whereas their study required both temperatures to be controlled at 34°C or 35°C to reduce heat exchange between the TM and the ambient environment. Those differences will change heat removal rates from the TM and heat gain from the environment, but

should not change the cooling efficiency. Our approach provided LCG heat removal rates and cooling efficiency as their method did, and, in addition, provided the thermal resistances required for efficiency prediction. This makes it possible to predict LCG performance and cooling efficiency for conditions or outer clothing ensembles other than the test conditions/outer ensembles. The equation for predicting LCG cooling rate developed by Teal, for instance, was limited to the ensemble and the environment in which the test was conducted (7).

Power inputs to the TM with active LCG and inactive LCG have been used to determine the LCG heat removal rate, i.e., Q_{sw}, since an early study by Fonseca (2,4–8). Q_{sw} measured is, in fact, not purely the heat removed from the human body by an LCG, but the extra heat taken away by an active LCG in comparison to an inactive LCG. This method implicitly assumes that the TM heat loss to the ambient environment (i.e., Q_a) with an active LCG is the same as Q_a with an inactive LCG. However, this assumption may cause a systematic error, depending on the LCG design (e.g., spacing) and test conditions (e.g., T_s, T_a). A measure to reduce or eliminate this error is to use a small $T_s - T_a$ difference or isothermal test condition, i.e., $T_s = T_a$. However, too small a difference will result in numerous small differences at or below the level of instrument detection to the point where no discrimination between conditions will be possible. The ASTM F1291 standard for measuring thermal insulation recommends a minimum heat flux of 20 $W \cdot m^{-2}$ (1). As a compromise, a difference for $T_s - T_a$ of 3°C was selected in our study to ensure the power input to each TM section was > 0.0 for all outer clothing ensembles, and, in the meantime, reduce the potential systematic error. Also, the measured Q_a may include some ventilation heat loss via the layered series of microenvironments. When the difference for $T_s - T_a$ increases, the potential error can be resolved only with more detailed measurement within the clothing layers and is considered in Eq. 1.

The results demonstrated the impact of outer clothing on the LCG cooling efficiency and heat removal rates in either the dry or wet (sweating) experiments. This indicated that LCG performance may vary with outer clothing ensembles. Together, Eq. 6 and thermal resistances in Table III can be used to estimate changes in cooling efficiency. If body armor with an insulation of ~0.388 $m^2 \cdot °C \cdot W^{-1}$ was worn over the CVO ensemble, using the thermal resistances for CVO shown in Table III and Eq. 6, the estimated cooling efficiency would be ~0.81 for the dry experiments and 0.87 for the wet experiments, respectively. The observed cooling efficiencies for similar LCG/outer clothing ensembles were 0.79–0.94 for dry experiments and 0.87–0.91 for wet experiments (2). Therefore, the prediction is reasonable.

Heat removal rates and cooling efficiency in wet (sweating) experiments are higher than in dry experiments, and Q_{sw} was about 2 times greater for wet vs. dry experiments. There are several mechanisms which contribute to this increase: 1) the cooling vest fabric was absorbing "sweat" in wet tests, thus enhancing heat transfer from the TM surface to flowing perfusate; 2)

TM skin was wet, increasing the heat conduction; 3) water vapor from the TM skin condensed onto the perfusate tubes, thus adding an extra avenue for heat transfer from the TM skin to the perfusing tubes (3). The heat gain from the ambient environment in wet experiments were, as shown in Fig. 2, also higher than in dry experiments, as the inner layers of the CVB and CVO clothing ensembles also absorbed "sweat" and became wet, thus enhancing heat conduction from the ambient environment to the flowing perfusate. Fig. 2 and 3 also show that when additional outer clothing was added, the total heat removal rates decreased in the dry experiments but unexpectedly slightly increased in the wet experiments. While all three mechanisms mentioned above might contribute to this observation, the most important one might be the vapor transfer and/or condensation onto the tube surface. Additional outer clothing (CV vs. CVO) reduced heat gain from the ambient environment by ~50%, and subsequently maintained perfusate temperature relatively lower over the course from inlet to outlet. This could significantly promote vapor condensation onto the perfusate surface and enhance heat loss from the TM to the perfusate. This heat loss increased by ~60% in the wet experiments but increased only by 31% in the dry experiments when comparing CV with CVO conditions at a T_{in} of 15°C.

Cooling efficiency is minimally influenced by T_{in}, although heat removal rates are dependent on T_{in}. When T_{in} was reduced from 25 to 15°C, both heat removal from the TM and heat gain from the ambient environment increased due to increases in the temperature differences, and, therefore, the cooling efficiency remained nearly constant. This is consistent with observations from previous studies (2,8). When the TM skin temperature (T_s) is equal to the ambient temperature (T_a), the gradients between T_w and T_a or T_s become equal. As the ratio now equals 1, it can be eliminated from Eq. 6. The simplified equation indicates that cooling efficiency is dependent on thermal resistances, i.e., R_{sw} and R_{aw}, but independent of T_{in}.

Wearing a cooling vest increased thermal and evaporative resistances. The additional resistance may increase heat stress in cases where the system does not work properly or the cooling vest is empty due to leakage. Values in Table I can be used as inputs for a thermal regulation model to predict the wearer's thermal responses when the MCS is not functional to assess the risk that the additional insulation may create.

Understanding the impact of outer clothing on cooling efficiency serves several purposes: 1) the cooling efficiency relationship can be used to improve the mathematical simulation of human responses with LCG/outer clothing combinations; 2) in physiological studies, it can be used to determine LCG heat loss from a human from the total heat removal, improving heat balance analyses; and 3) information on cooling efficiency can help engineers convert physiological cooling requirements into system specifications for the cooling unit.

In this study, tests were conducted with one set of environmental conditions (i.e., constant values for temperature, humidity, and wind speed) without any adjustment for solar radiation. The addition of a solar component could significantly impact the efficiency of an LCG system as radiation may be an important factor in field environments. Further tests and theoretical analysis would be required to investigate how this might affect the cooling efficiency in an operational scenario.

Conclusion

This study used an integrated approach of theoretical analysis and sweating thermal manikin testing to investigate the impact of outer clothing and perfusate inlet temperatures on the cooling efficiency of a liquid cooling garment. The insulation of an outer clothing ensemble reduced the heat gain from the environment and thus increased the cooling efficiency. The perfusate inlet temperature had minimal influence on the cooling efficiency. The equations developed can be used to predict the cooling efficiency and heat removal rates under wider environmental conditions.

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